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Response of Wild Rice to Selected Aquatic Herbicides

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ABSTRACT: The invasion of exotic plants such as Eurasian watermilfoil (*Myriophyllum spicatum* L.) has contributed to the decline and displacement of native wild rice (*Zizania aquatica* L.) populations in many U.S. water bodies. Wild rice is a popular food source for both man and animal and provides important habitat for waterfowl, invertebrates, and fish. Herbicides can be successfully used to manage invasive weeds such as Eurasian watermilfoil; however, the potential impacts of such chemical management techniques on native plants (including wild rice) are not well documented. This outdoor tank study was conducted to examine the effects of several aquatic herbicides on the growth and survival of wild rice and to determine whether nontarget herbicide efficacy is influenced by wild rice growth stage.

Aquatic formulations of the herbicides diquat, endothall, fluridone, and 2,4-D were applied at varying rates and contact times to three growth stages of wild rice. Results showed that degree of herbicide injury varied with plant growth stage. Wild rice treated at younger growth stages (early tillering or seedling stages) was more sensitive to chemical treatment than plants treated at later stages of development. Regardless of product or rate, herbicide treatment did not affect wild rice plants when applied at the mature growth stage (late tillering and flowering). Of the herbicides evaluated, wild rice was most sensitive to 2,4-D. Rates as low as 1 mg 2,4-D L^{-1} significantly inhibited tiller, seedhead, and dry weight biomass production in young wild rice. Dry weight of young wild rice was also reduced following exposure to endothall, diquat, and fluridone; however, seedhead and tiller production was not influenced by these products.

The results of this study suggest that wild rice is most resistant to herbicides applied to the water column when plants are mature or in the late flowering stages of development. Coordinating chemical applications for Eurasian watermilfoil control with resistant growth stages of wild rice will minimize herbicide injury to this desirable native plant species.

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Preface

The work reported herein was conducted as part of the Aquatic Plant Control Research Program (APCRP). The APCRP is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL), Vicksburg, MS. Major support was also provided by the U.S. Army Engineer District, Detroit, coordinated through Mr. Charles Uhlarik and Mr. Joe Wanielista. Funding was provided under Department of the Army Appropriation No. 96X3122, Construction General. Mr. Robert C. Gunkel, Jr., was Program Manager, APCRP. Program monitor during this study was Mr. Timothy R. Toplisek, HQUSACE.

The Principal Investigator of this work was Dr. Kurt D. Getsinger, Environmental Processes Branch (EPB), Environmental Processes and Engineering Division (EPED), EL. This work was conducted and the report prepared by Dr. Linda S. Nelson, EPB, Ms. Chetta S. Owens, Analytical Services, Inc., Huntsville, AL, and Dr. Getsinger.

Technical reviews of this report were provided by Ms. Lee Ann Glomski, Purdue University, West Lafayette, IN, and Mr. John Skogerboe, EPB. Thanks are extended to Mr. David Honnell, North Texas State University, Denton, TX, for conducting herbicide residue analyses, and to Ms. Glomski for assisting in the initial setup of this experiment. Thanks also to Dr. Dennis L. Brandon, Environmental Risk Assessment Branch, EPED, for providing guidance on statistical analysis of the data.

This work was performed under the general supervision of Dr. Terrence M. Sobecki, Chief, EPB; Dr. Richard E. Price, Chief, EPED; and Dr. Elizabeth C. Fleming, Acting Director, EL.

COL James R. Rowan, EN, was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Background

Eurasian watermilfoil (*Myriophyllum spicatum* L.) (hereafter referred to as milfoil) is an exotic submersed plant that has invaded many lakes, rivers, and reservoirs throughout the United States. Once established, this plant becomes a nuisance due to its rapid growth rate, ability to form dense, monotypic stands with extensive surface canopies, and aggressiveness in displacing desirable native vegetation (Smith and Barko 1990, Madsen 1997). Results of a vegetation survey conducted in 1999 (Pullman 2000) confirmed that more than 4,000 ha of Houghton Lake, Michigan, had become infested with milfoil. Concern over the nuisance levels of this weed prompted local officials to review options for control (Getstinger et al. 2002). Herbicides were selected as the best whole-lake management tactic available for this site, and in 2002, a low-dose treatment with the herbicide fluridone ensued (Poovey et al. 2003). This treatment was designed to selectively control >80 percent of the milfoil in the entire lake while minimizing injury to nontarget aquatic vegetation.

One of the concerns for utilizing herbicides to manage milfoil infestations in this lake was the potential for nontarget impacts on native, desirable plant species that share the same habitat. One species of particular interest is wild rice (*Zizania* L.). Wild rice is an emergent aquatic grass that grows in shallow areas of lakes and slow-moving rivers throughout eastern and north-central North America (Aiken et al. 1988). There are four species in the genus *Zizania*, three of which are native to North America: *Z. palustris* L., *Z. aquatica* L., and *Z. texana* Hitchcock (Aiken et al. 1988, Oelke 1993, Duvall 1995). Both *Z. palustris* and *Z. aquatica* are annuals and are widespread in distribution (Aiken 1988), whereas *Z. texana* is a perennial and grows exclusively in the San Marcos River in Texas (Terrell et al. 1978, Aiken et al. 1988). Several distinct varieties are recognized within the two annual species; however, there are considerable differences of opinion as to their taxonomic treatment (Fassett 1924, Hitchcock 1951, Gleason and Cronquist 1963, Warwick and Aiken 1986, Counts and Lee 1987, Aiken et al. 1988, Duvall 1995). To add to the confusion, the name "wild rice" is habitually used as a common name for the entire genus (Oelke et al. 1992). The species of interest in Houghton Lake is identified as *Z. aquatica* (Ustipak 1995). For this report, any reference to wild rice will pertain specifically to the species *Z. aquatica*, unless otherwise noted.

Wild rice has commercial value as well as provides food and habitat for waterfowl and other vertebrates (Hitchcock 1951, Evenson and Hopkins 1973,

Hayes et al. 1989, Ustipak 1995). Historically, wild rice was an important food item in the diet of many North American Indian tribes (Aiken et al. 1988, Oelke 1993). Until recently, much of the waterfowling and sport fishing activities in Houghton Lake were centered around wild rice habitat (Ustipak 1995). Years ago, wild rice was the dominant emergent plant found in Houghton Lake; however, many of these stands were significantly depleted in the 1930s through the 1950s as a result of increased harvesting activities (Getsinger et al. 2002). According to Ustipak (1995), wild rice populations continued to decline in Houghton Lake during the late 1980s, and by the early to mid-1990s, were nearly nonexistent. Ustipak (1995) speculated that recent declines were the result of numerous factors including water level fluctuations, changes in water chemistry, accumulation of phytotoxic compounds in lake sediments, increased wave action due to boat traffic and bulk heading of shorelines, nutrient deficiencies, and pathogens. Increased populations of invasive exotic species such as milfoil, purple loosestrife (*Lythrum salicaria* L.), and flowering-rush (*Butomus umbellatus* L.) may also be to blame for displacement of wild rice populations.

While there is some information in the literature concerning weed control practices in commercial wild rice (*Z. palustris*) production (Clay and Oelke 1990, Oelke and McClellan 1991), little information exists specifically describing effects of aquatic herbicides on wild rice when used in lake management to control invasive species such as milfoil. Therefore, the objectives of this study were to evaluate the effects of herbicide treatments recommended for milfoil control on the growth and survival of wild rice, and to determine whether nontarget herbicide efficacy on wild rice is influenced by plant growth stage. Information provided by this evaluation will be useful in planning milfoil management practices where wild rice is a nontarget component of the vegetative community.

Materials and Methods

This study was conducted in large, oval (0.63 m tall by 1.40 m wide by 1.6 m long) Rubbermaid™ tanks (Newell Rubbermaid Company, Wooster, OH) located at the U.S. Army Engineer Research and Development Center's Lewisville Aquatic Ecosystem Research Facility (LAERF), Lewisville, TX. Each tank housed a total of 16 pots of plants representing three different growth stages (mature, young, and seedling) of wild rice.

The seed and plant materials (sold as *Z. aquatica*) used in this study were obtained from Wildlife Nurseries, Oshkosh, WI. To obtain the three different growth stages for this experiment, plants were initiated at different times using the following procedures:

a. *Mature growth stage.* Mature plants were grown from seeds that were initially planted in 10-cm peat-pots filled with a mixture (3:1) of pond sediment and peat amended with 1 g ammonium sulfate fertilizer. Pots were placed in a shallow culture tank filled with natural lake water to a depth of 8 cm. The culture tank was covered with a canopy of 20-percent shade cloth. After 3 weeks of growth, plants of equal size

and leaf number were transplanted into 5-L pots (one plant per pot) filled with pond sediment amended with 4 g ammonium sulfate plus one fertilizer briquette (20-10-5; Agriform™, Marysville, OH) and were placed in the large, experimental tanks.

b. *Young growth stage.* Wild rice plants defined herein as the "young" growth stage were initiated from plant cultures shipped overnight from Wildlife Nurseries. These plants were 45 cm in length (as measured from leaf tip to root base), with two to three aerial leaves (leaf tips had been clipped for shipping), and had roots measuring 10 to15 cm in length. Plants of equal size were immediately transplanted into fertilizer-amended, sediment-filled pots (one plant per 5-L pot) and placed in the experimental tanks as described above.

c. *Seedling growth stage.* Plants used for the seedling growth stage were initiated from seed. Seeds were removed from cold storage and placed in a shallow pan of de-ionized water under lighted, laboratory conditions to induce germination. Seeds germinated in 2 to 3 days under these conditions. Three germinated seeds of equal size were planted 5 cm deep into 5-L pots filled with saturated sediment (same sediment and fertilization as described above). Prior to herbicide application, each pot was thinned to one seedling per pot.

All plants were allowed to acclimate for 10 days in the experimental tanks prior to herbicide treatment. At the time of herbicide treatment, mature plants (four pots per tank) had produced tillers and were beginning to flower; young plants (six pots per tank) had two to three aerial leaves and were in the early tillering phase but were not flowering; and seedlings (six pots per tank) had one to two floating leaves (no aerial leaves or tillers). The water level in each tank was maintained at a depth of approximately 40 cm. Once a week, the insecticide, temephos (phosphorothioic acid, O,O'-(thiodi-4,1-phenylene) bis (O,O'-dimethyl) phosphorathioate), was applied at a rate of 40 μl Abate™ formulation (Clarke Mosquito Control Products, Inc., Roselle, IL) per tank to control aquatic insect larvae that feed on plants. Water quality and chemical composition of lake water and pond sediments used in this study are described in Smart et al. (1995).

Fluridone, endothall, diquat, and 2,4-D were evaluated against wild rice. These herbicides were selected for evaluation since they are products approved in Michigan for control of milfoil. Table 1 summarizes herbicides, formulations, application rates, and contact times tested in this study. Application rates represent low and high herbicide use rates as recommended by each product label for milfoil control. Contact times were selected based on herbicide concentration exposure time relationships for milfoil control, and were previously developed in laboratory studies (Green and Westerdahl 1990, Netherland et al. 1991, 1993, Getsinger and Netherland 1997, Skogerboe and Getsinger 2002).

All herbicides were applied directly to the water in each tank to simulate application procedures for a submersed-plant treatment. Calculated volumes of each formulation were mixed in 1 L of de-ionized water, then poured evenly onto the water surface of each tank to achieve the desired treatment concentration.

Table 1
Herbicides, Formulations, Rates of Application, and Contact Times Evaluated Against Wild Rice (*Zizania aquatica* L)

Herbicide (Chemical Name)	Formulation	Rate of application mg L^{-1}	Contact time[1] days
Diquat (6,7-dihydrodipyridol [1,2-α:2',1'-*c*]pyrazinediium ion)	REWARD™ [2]	0.50 1.00	3 3
Endothall (7-oxabicyclo[2.2.1] heptane-2,3-dicarboxylic acid)	Aquathol™ [3] K	1.00 2.00	3 3
Fluridone (1-methyl-3-phenyl-5-[3-(triflurormethyl)phyenyl]-4(1*H*)-pyridinone)	Sonar™ [4] A.S.	0.006[5] 0.012	28 28
2,4-D ((2,4-dichlorophenoxy) acetic acid)	DMA™ [6] 4 IVM	1.00 2.00	7 7

Note: All herbicides were applied to the water column to achieve the listed rate of application. Rates are those recommended for controlling Eurasian watermilfoil (*Myriophyllum spicatum* L.) in Michigan lakes.

[1] Contact time is the length of time that plants were exposed to herbicide treatment in the water. Following the designated contact time, herbicide-treated water was removed from each experimental tank and tanks were refilled with fresh, untreated water. Fluridone was the only herbicide evaluated with a sustained contact time for the duration of the study.

[2] Tradename of Syngenta Professional Products, Wilmington, DE.

[3] Tradename of Cerexagri, Inc., Philadelphia, PA.

[4] Tradename of SePRO Corporation, Carmel, IN.

[5]Equivalent to 6 μg L^{-1}.

[6]Tradename of Dow AgroSciences LLC, Indianapolis, IN.

After each designated contact time (Table 1), the herbicide-treated water was removed from each tank and replenished with fresh lake water for the remainder of the experiment.

Water samples were collected from each tank approximately 2 hr following herbicide application and subsequently analyzed for herbicide residues to verify treatment rates. Water samples were also collected following the drain procedure to confirm removal of herbicide residues from each treated tank (endothall-, diquat-, and 2,4-D-treated tanks only). Since the contact time for fluridone extended the length of the experiment, fluridone-treated tanks did not undergo the draining procedure. With the exception of endothall, all of the residue analyses were conducted at the LAERF laboratory using high performance liquid chromatography (HPLC) methodologies. Analytical equipment other than HPLC was required for detection of endothall residues; therefore, these samples were shipped to the manufacturer for analysis. The results of the endothall analyses were not available at the time of this report.

The experiment was maintained for 4 weeks following herbicide application. At the end of the study, plant height (length from the sediment surface to the tip of the longest leaf) and the number of seedheads and tillers were recorded for each plant. Once measurements were recorded, plants from each pot were

clipped at the sediment surface, dried to a constant weight at 70 °C, and weights recorded.

The treatments were randomly assigned to tanks (27 total) and were arranged in a randomized block design with three replicates. Data were subjected to analysis of variance (ANOVA) procedures using SAS (SAS Institute 1988). The Shapiro-Wilk's test for normality (Conover 1980) was performed, and Cochran's test was used to test for equality of variances (Winer 1971). Seedhead and tiller data were transformed ($\sqrt{x} + 1$) to normalize data (Snedecor and Cochran 1980), and dry weight data were $\log_{10}$ transformed to meet the normality and equality of variances assumptions. The Waller-Duncan *k*-ratio *t* Test was used to compare treatment means at the $\alpha = 0.05$ level of significance. Nontransformed data are presented.

2 Results and Discussion

Analysis of water samples following herbicide application showed that targeted treatment rates were achieved for diquat and 2,4-D (Table 2). Fluridone concentrations were slightly higher (by 25 to 31 percent) than the intended application rates; however, concentrations were well within the recommended label rate of application for milfoil treatment. Water samples collected following the drain procedure showed that herbicide residues were removed following each designated contact time.

Table 2
Concentration of Diquat, Fluridone, and 2,4-D in Water Sampled After Herbicide Application to Verify Treatment Rates and After Draining Procedures to Verify Removal of Herbicide-Treated Water

Herbicide	Target Treatment Rate mg L^{-1}	Time of Sample Collection	
		Post Application, mg L^{-1}	Post Drain, mg L^{-1}
Diquat	0.5 1.0	0.50 (0.04) 1.30 (0.21)	0.00 (0.00) 0.02 (0.03)
Fluridone	0.006 0.012	0.0079 (0.0004) 0.0150 (0.0015)	NS[1] NS
2,4-D	1.0 2.0	0.99 (0.09) 1.82 (0.14)	0.08 (0.01) 0.14 (0.01)

Note: Water samples were analyzed via HPLC. Numbers are means (±SD) of three replicates.
[1] NS = No sample; fluridone tanks were not drained during the experiment so that a 28-day contact time (static exposure) could be maintained.

Herbicide effects on plant height, seedhead number, tiller number, and dry weight of wild rice grown at three growth stages are summarized in Tables 3-5. Results showed that herbicide treatment did not significantly affect wild rice plants when applied at the mature growth stage. Regardless of product or rate, plant height, production of tillers and seedheads, and dry weight of mature plants were not statistically different compared to untreated mature plants.

In contrast, plants treated at younger growth stages were more sensitive to chemical treatment. Number of tillers produced on young wild rice was reduced 59 to 69 percent when exposed to 1 or 2 mg L^{-1} 2,4-D (Table 4). These 2,4-D-treated plants also produced 51 percent fewer seedheads compared to untreated controls. Dry weight biomass of young plants was significantly inhibited by 2,4-D (both rates), endothall at 2 mg L^{-1}, and 0.5 mg L^{-1} diquat (Table 5). Effects were similar among these treatments, with reductions ranging from 35 to 48 percent that of untreated plants.

Table 3
Effect of Herbicide Treatments on Plant Height of Wild Rice (*Zizania aquatica* L.) Grown at Three Growth Stages[1]

Herbicide	Treatment Rate mg L^{-1}	Plant Height, cm		
		Mature	Young	Seedling
Control	0	107.2 a	132.8 a	92.5 a
Fluridone	0.006	108.7 a	140.5 a	63.5 a
	0.012	105.2 a	122.9 a	82.3 a
Endothall	1.0	95.5 a	120.4 a	63.2 a
	2.0	104.4 a	121.4 a	53.8 a
2,4-D	1.0	116.8 a	116.8 a	57.7 a
	2.0	98.6 a	112.8 a	46.5 a
Diquat	0.5	111.5 a	106.9 a	75.5 a
	1.0	98.3 a	115.6 a	57.9 a

Note: Measurements were recorded 4 weeks after treatment.
[1] Means in a column followed by the same letter do not differ at $\alpha = 0.05$.

Table 4
Effect of Herbicide Treatments on Number of Seedheads and Tillers Produced Per Plant for Three Growth Stages of Wild Rice (*Zizania aquatica* L.)[1]

Herbicide	Treatment Rate mg L^{-1}	Number of Seedheads Per Plant		
		Mature	Young	Seedling
Control	0	2.9 a	3.3 a	1.5 a
Fluridone	0.006	3.4 a	3.4 a	0.9 a
	0.012	3.3 a	3.2 a	1.4 a
Endothall	1.0	2.9 a	3.2 a	1.0 a
	2.0	2.9 a	2.6 ab	1.0 a
2,4-D	1.0	2.8 a	1.6 b	1.0 a
	2.0	3.8 a	1.6 b	0.8 a
Diquat	0.5	3.1 a	2.8 a	1.1 a
	1.0	3.4 a	2.9 a	1.3 a
		Number of Tillers Per Plant		
Control	0	2.3 a	2.9 a	0.9 a
Fluridone	0.006	2.4 a	2.7 a	0.1 a
	0.012	2.3 a	2.4 a	0.7 a
Endothall	1.0	1.8 a	2.7 a	0.4 a
	2.0	1.9 a	2.1 ab	0.3 a
2,4-D	1.0	1.8 a	0.9 c	0.4 a
	2.0	2.8 a	1.2 bc	0.4 a
Diquat	0.5	2.1 a	2.2 ab	0.5 a
	1.0	2.5 a	2.4 a	0.7 a

Note: Measurements were recorded 4 weeks after treatment.
[1] Means in a column followed by the same letter do not differ at $\alpha = 0.05$.

Table 5
Effect of Herbicide Treatments on Dry Weight of Wild Rice (*Zizania aquatica* L.) Grown at Three Growth Stages[1]

Herbicide	Treatment Rate mg L^{-1}	Dry Weight, g		
		Mature	Young	Seedling
Control	0	4.5 a	6.5 a	1.5 a
Fluridone	0.006 0.012	5.9 a 4.6 a	6.5 a 5.0 abc	0.7 bcd 1.3 ab
Endothall	1.0 2.0	3.8 a 3.8 a	5.7 ab 4.1 bc	0.7 bcd 0.5 cd
2,4-D	1.0 2.0	5.3 a 3.7 a	3.6 c 3.4 c	0.6 bcd 0.4 d
Diquat	0.5 1.03	5.1 a 4.9 a	4.2 bc 5.0 abc	1.0 abc 0.9 a-d

Note: Measurements were recorded 4 weeks after treatment.
[1] Means in a column followed by the same letter do not differ at $\alpha = 0.05$.

Plant height and number of seedheads and tillers of seedling wild rice were unaffected by chemical treatment (Tables 3 and 4); however, final plant biomass was significantly reduced following application of several herbicides (Table 5). Compared to untreated seedlings, plants treated with 0.006 mg L^{-1} fluridone and 1 and 2 mg L^{-1} of either endothall or 2,4-D reduced seedling weight by 53 to 73 percent. Effects were statistically similar among these treatments. Neither rate of diquat nor the high rate of fluridone influenced seedling dry weight. It is unknown why the lower rate of fluridone inhibited plant weight while doubling the rate showed no effect.

Although there is no information in the literature addressing the effects of diquat and endothall on wild rice, the results reported here for 2,4-D and fluridone are similar to those reported by other researchers. Miller (1994) found that fluridone at low rates (0.002 and 0.004 mg L^{-1}) did not affect dry weight of wild rice (*Z. aquatica* var. *aquatica*) when applied to water with plants at the floating-leaf growth stage (similar to seedling stage in this study). Higher rates of fluridone ($\geq$0.008 mg L^{-1}) caused significant decreases (30 to 81 percent) in dry weight biomass in these experiments. Loss of biomass was attributed to a decrease in both number and size of roots and aerial leaves. Miller (1994) also evaluated the effect of 2,4-D on floating-leaf stage wild rice and found that rates as low as 0.4 mg L^{-1} significantly reduced dry weight by 24 percent. Higher rates (0.8, 1.6, and 3.2 mg L^{-1}) of 2,4-D resulted in greater biomass losses (67, 88, and 94 percent, respectively).

Clay and Oelke (1990) evaluated 2,4-D (amine salt formulation) for weed control in commercial wild rice (*Z. palustris*) production and found that 2,4-D applied at rates as low as 1.1 kg ha^{-1} to wild rice at the two-aerial-leaf stage (five leaves total: two above the water, one floating, two below the water) severely injured plants. Higher 2,4-D rates significantly reduced grain yield. Similarly, Oelke and McClellan (1991) showed that applying 2,4-D amine (0.84 kg ha^{-1} and higher) to wild rice in the mid to late tillering growth phase significantly injured plants and reduced grain yield 32 to 56 percent. Consistent with the findings herein, Oelke and McClellan (1991) did not observe 2,4-D effects on plant

height. While the application method used in the aforementioned studies differed from methods used here (foliar spray vs. treatment of the water), the results of all of these studies indicated that wild rice is sensitive to 2,4-D when applied to young, actively growing plants.

It was not surprising that greater sensitivity to herbicides applied to wild rice was observed at younger growth stages. It is well known that age and stage of development can influence plant sensitivity to herbicides (Åberg and Steckó 1976, Ross and Lembi 1985). In general, young, actively growing plant tissues are more susceptible to chemical treatment than mature plants (Klingman and Ashton 1982, Ross and Lembi 1985). This is due to the fact that rapid growth temporarily depletes or exhausts plants of their carbohydrate reserves making them more susceptible to herbicides and less likely to recover from injury due to herbicide toxicity (Åberg and Steckó 1976, Ross and Lembi 1985). Understanding age or developmental differences among plants can be used to achieve herbicide selectivity (Åberg and Steckó 1976, Ross and Lembi 1985). In other words, treatment selectivity can be obtained if herbicides are applied at the time when the nontarget plant (such as wild rice) is most resistant and the target weed (such as milfoil) is most susceptible.

In summary, results of this study showed that, of the herbicides evaluated, young wild rice was most sensitive to 2,4-D. Under these experimental conditions, application of 1 mg L^{-1} 2,4-D to the water column not only significantly reduced the reproductive capacity of young wild rice plants (lower tiller and seedhead numbers), but also reduced dry weight biomass. Although actual seed weight, number, and viability were not recorded in this study, reduced tillering and seedhead production can be correlated to lower grain yields (Aiken et al. 1988). Therefore, it can be concluded that application of 2,4-D to the water column while wild rice is in the early stages of tillering may result in a significant loss of seeds produced. This in turn may result in further decline of existent plant populations since seed is the method of propagation for this annual plant species. Fluridone, endothall, and diquat may also reduce plant vigor as evidenced by decreased biomass following exposure to young rice plants. Treatment of the water column with fluridone, diquat, endothall, and 2,4-D, at rates sufficient to control milfoil, did not negatively impact the growth and seedhead production of mature wild rice plants.

Results of this study suggest that wild rice is most resistant to aquatic herbicides applied to the water column when plants are mature or in the late flowering stages of development. Coordinating chemical applications for milfoil control with resistant growth stages of wild rice may minimize herbicide injury to this desirable plant species.

3 Conclusions

Based on the results of this study, the following conclusions can be made concerning the impact of aquatic herbicides on wild rice:

a. Degree of herbicide injury to wild rice varies with plant growth stage. Aquatic herbicides do not significantly affect wild rice when applied to water containing mature plants (mid to late flowering); however, plants treated at younger growth stages (seedlings with floating leaves and young plants with aerial leaves and early tillers) are sensitive to herbicide application. Results suggest that wild rice is most resistant to herbicide injury when submersed applications are made during late stages of plant development.

b. Of the herbicides evaluated in this study, wild rice is most susceptible to 2,4-D. Applying 2,4-D to water when plants are in the early to mid tillering stage of development results in reduced tiller and seedhead production. Plant biomass of young and seedling stage wild rice is also suppressed by 2,4-D.

c. Endothall, fluridone, and diquat also inhibit plant biomass of actively growing wild rice plants. Seedhead and tiller production are not influenced by these products.

d. Regardless of growth stage, plant height of wild rice is not sensitive to herbicide exposure.

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14. ABSTRACT

The invasion of exotic plants such as Eurasian watermilfoil (*Myriophyllum spicatum* L.) has contributed to the decline and displacement of native wild rice (*Zizania aquatica* L.) populations in many U.S. water bodies. Wild rice is a popular food source for both man and animal and provides important habitat for waterfowl, invertebrates, and fish. Herbicides can be successfully used to manage invasive weeds such as Eurasian watermilfoil; however, the potential impacts of such chemical management techniques on native plants (including wild rice) are not well documented. This outdoor tank study was conducted to examine the effects of several aquatic herbicides on the growth and survival of wild rice and to determine whether nontarget herbicide efficacy is influenced by wild rice growth stage.

Aquatic formulations of the herbicides diquat, endothall, fluridone, and 2,4-D were applied at varying rates and contact times to three growth stages of wild rice. Results showed that degree of herbicide injury varied with plant growth stage. Wild rice treated at younger growth stages (early tillering or seedling stages) was more sensitive to chemical treatment than plants treated at later stages of development. Regardless of product or rate, herbicide treatment did not affect wild rice plants when applied at the mature growth stage

(Continued)

15. Subject Terms

	Diquat	Fluridone	2,4-D
Aquatic plant management	Endothall	Herbicide	*Zizania aquatica*
Chemical control	Eurasian watermilfoil	*Myriophyllum spicatum*	

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(late tillering and flowering). Of the herbicides evaluated, wild rice was most sensitive to 2,4-D. Rates as low as 1 mg 2,4-D L^{-1} significantly inhibited tiller, seedhead, and dry weight biomass production in young wild rice. Dry weight of young wild rice was also reduced following exposure to endothall, diquat, and fluridone; however, seedhead and tiller production was not influenced by these products.

The results of this study suggest that wild rice is most resistant to herbicides applied to the water column when plants are mature or in the late flowering stages of development. Coordinating chemical applications for Eurasian watermilfoil control with resistant growth stages of wild rice will minimize herbicide injury to this desirable native plant species.